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Design of a perfect balance system for active upper-extremity exoskeletons

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***Abstract*—Passive gravity compensation in exoskeletons significantly reduces the amount of torque and energy needed from the actuators. So far, no design has been able to achieve perfect balance without compromising the exoskeleton characteristics. Here we propose a novel design that integrates an existing statically-balanced mechanism with two springs and four degrees of freedom into a general-purpose exoskeleton design, that can support any percentage of the combined weight of exoskeleton and arm. As it allows for three rotational degrees of freedom at the shoulder and one at the elbow, it does not compromise exoskeleton characteristics and can be powered with any choice of passive or active actuation method. For instance, with this design a perfectly balanced exoskeleton design with inherently safe, passive actuators on each joint axis becomes possible. The potential reduction in required actuator torque, power and weight, simplification of control, improved dynamic performance, and increased safety margin, all while maintaining perfect balance, are the major advantages of the design, but the integrated systems does add a significant amount of complexity. Future integration in an actual exoskeleton should prove if this tradeoff is beneficial.**

Keywords— rehabilitation robotics, balancing mechanism, exoskeleton, weigh-support, passive gravity compensation, upper extremity.

I. INTRODUCTION

Several patient-friendly robots are currently available and used for a wide range of neuromusculoskeletal impairments as diagnostic and therapeutic aids in upper limb rehabilitation [1][2]. Robot-assisted therapy is considered to be as good or better than conventional therapy [3][4], less labor intensive for the therapists and more challenging for patients. Furthermore, this technology can provide the clinical and scientific community with objective and quantitative data for the systematic evaluation of the patient's progression through the rehabilitation process.

An important aspect of rehabilitation robotics is gravity compensation. For comfort reasons the patient should not carry or even feel the weight of the robot. Additionally, compensating the weight of the human arm has been proved to have a positive effect on the progress of rehabilitation [5] [6]. Recent studies have shown that gravity support leads to an increased range of motion (ROM) and decreases strength of involuntary coupling between shoulder and elbow joints [7] [8].

Fig. 1. The perfect balance system for active upper-extremity exoskeletons. This system is well suited for providing the compensation forces to support the combined weight of an active exoskeleton and of the patient's arm. The mechanism follows the natural rotations of the human arm with three degrees of freedom at the shoulder joint and one degree of freedom at the elbow joint. Endo-exorotation is possible through the virtual rotation mechanism, but also a circular guiding rail could be used. The Pronation-supination is possible through the rotational semicircular guiding rail at the wrist cuff.

Generally, current rehabilitation robots provide gravity support actively using actuators. Rehabilitation robots that implement this strategy are for example the Limpact [9], the ARMin [10], the IntelliArm [11] and the MGA-Exoskeleton [12]. Gravity forces can also be compensated passively using counter weights [13] or elastic elements such us rubber bands [14] or springs [15][16]. Counter weights have the disadvantage of adding considerable mass and inertia into the system. Rubber bands are more compact (i.e. higher energy per volume) than springs but they present nonlinear behavior.

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Passive weight-support offers clear advantages over conventional active methods that require large amounts of actuator torque and energy to compensate gravity. The use of a passive weight compensation mechanism can simplify the control, reduce the actuator torque demand, lower the power consumption and lead to improved dynamic performance of the rehabilitation robot. Furthermore, passive gravity compensation is considered to be inherently safer than active methods [17]. Although this strategy requires an additional mechanism and adds more complexity to the design, the potential reduction of size and weight are major advantages of passive gravity compensation that are appreciated by engineers, patients and rehabilitation specialists.

This paper describes the development of a perfect balance system for active upper-extremity exoskeletons. The proposed mechanism is well suited for providing compensation forces to support the combined weight of the patient's arm and still allows for direct control of the shoulder and elbow rotations when active actuators are added. The mechanism follows the natural rotations of the human arm with three rotational degrees of freedom (DOF) at the shoulder and one at the elbow joint (Fig. 1).

II. BACKGROUND

In this section the gravity compensation strategies of some current exoskeletons are discussed. The working principles of the T-Wrex [15] mechanism and the Anthropomobile Balanced Arm [17][18] are described in more detail as they are specially relevant for the proposed design of the passive balance system. The reader is referred to [19] for a theoretical study of a passive weight support mechanism capable of balancing the arm without using any auxiliary links (i.e. parallelograms).

A. *Current exoskeletons*

The Dampace [20] is a passive exoskeleton with controlled braking on the three rotational axes of the shoulder and one of the elbow (the conventional 3,1 configuration). The weight support is provided by three independent balanced springs mechanisms that are attached via an overhanging cable system to the wrist, elbow and shoulder and deliver constant gravity compensation forces through the entire arm ROM.

The Limpact [9] is an active exoskeleton actuated with rotational hydro-elastic motors. In this case, the actuators provide the gravity compensation. The Limpact also presents a 3,1 configuration of the DOFs with one actuator for each DOF. Both the Dampace and the Limpact deal with the additional translational DOFs in the shoulder using free-translating yet torsional stiff platforms.

The ARMin II [10] is also an active exoskeleton with a 3,1 configuration that has both counterweights and an active gravity compensation system driven by linear actuators. In the ARMin III [21] gravity compensation is provided using a hybrid method. The weight of the upper arm is compensated passively, while the weight of the lower arm is compensated actively.

Exoskeletons such as the Dampace the Limpact and the ARMin, that present a 3,1 configuration of the DOFs, can mimic closely the natural rotations of the human arm and allow the upper arm segment of the exoskeleton to be directly connected to the human arm.

B. *T-Wrex solution*

The T-Wrex [15] is a passive exoskeleton with four DOF, two at the shoulder and two at the elbow (2,2 configuration). This 2,2 configuration is needed to keep the two gravity compensation mechanisms upright at all times, but restricts the range of motion of the arm and only allows loose connections between the upper arm segment of the exoskeleton and the human arm. The gravity compensation mechanism of the T-Wrex has one parallelogram, one beam and two springs (Fig. 2), which create two basic gravity equilibrators in series, where the vertical spring forces ($F_{s1,y}$ and $F_{s2,y}$) provide the gravity compensatory forces in every position independently of the angle φ_i. The spring force, $F_{si,}$ is decomposed in the vertical axis ($F_{si,y}$) and along the beam ($F_{si,x}$). The vertical spring force, $F_{si,y}$, is constant and always equal to the distance a_i times the spring stiffness k_i:

$$F_{si,y} = a_i k_i \tag{1}$$

Since the moments about the mechanism are only dependent on the vertical spring force ($F_{si,p}$), the following equations apply:

$$m_i g L_i = r_i k_i a_i \tag{2}$$

$$F_{mi} = a_i k_i \frac{r_i}{L_i} \tag{3}$$

where m_i is the mass, g is the gravitational force, r_i is the projection of the spring length along the beam, L_i is the distance between the pivot and the mass, a_i is the vertical distance between the joint and attachment of the spring, and F_{mi} is the weight force of m_i.

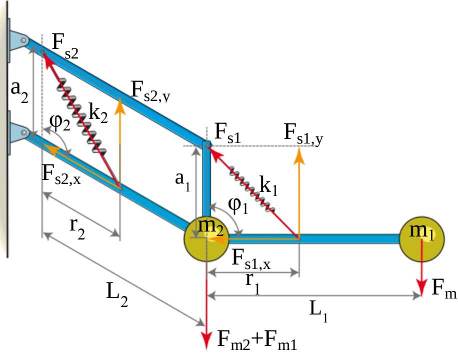

Fig. 2. Diagram of the T-Wrex exoskeleton which can be conceived as two basic gravity equilibrators in series. The forces F_{mi} are independent of the angle φ_i, because the vertical spring forces $F_{si,y}$ are always equal to the distance a_i times spring stiffness k_i.

C. *Anthropomobile Balanced Arm*

The Anthropomobile Balanced Arm (ABA) designed by Herder and Tuijthof [17][18], is a statically balance mechanism that resembles the movements of the human arm with a 3,1 configuration (Fig. 4). The ABA can be decomposed into two gravity equilibrators (Fig. 3).

The mechanism depicted in Fig. 3a represents the upper arm, and can be conceived as a basic gravity equilibrator with three DOFs (universal joint). The forearm mechanism is depicted in Fig. 3b with one DOF (hinge joint). In order to maintain static balance of the forearm, the spring k_1 needs to be independent of the position of the upper arm. Therefore a new parallelogram is added (similar to the mechanism of the Anglepoise® desk lamp; Fig. 4a). And the spring k_1 is located under the shoulder joint (Fig. 4b). Note that for this case (2) is valid as well.

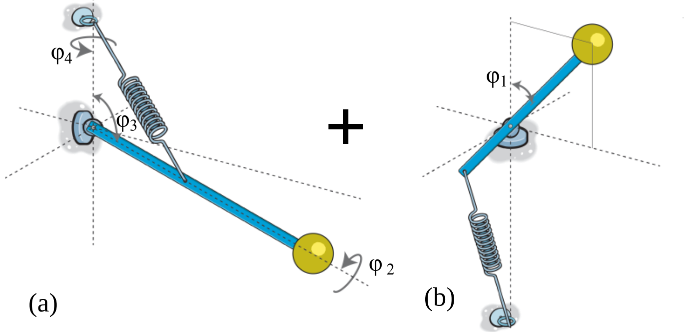

Fig. 3. The two gravity equilibrators that compose the ABA. (a) represents the upper arm with three DOFs and (b) represents the forearm with one DOF.

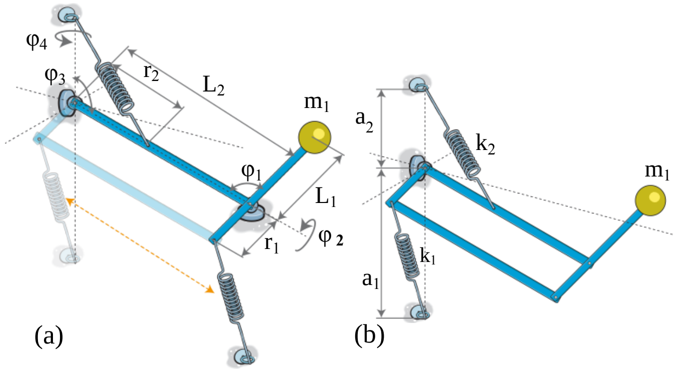

Fig. 4. The ABA mechanism which is derived from two gravity equilibrators shown in Fig. 3. (a) ABA with the spring k_1 attached directly at the forearm segment . (b) ABA with the parallelogram mechanism that allows to shift spring k_1 under the shoulder joint.

D. *Configuration of the DOF*

The human arm has a 3,1, configuration with three DOF in the shoulder joint and one DOF in the elbow joint (without considering pronation-supination rotation). Exoskeletons, such as the Dampace the Limpact or the ARMin, that feature a 3,1 configuration of the DOF, are able to mimic closer the natural rotations of the human arm than exoskeletons, such as the T-Wrex, with a 2,2 configuration (i.e. 2 DOF in the shoulder and 2 DOF in the elbow) which do not allow internal-external rotation of the upper arm.

III. REQUIREMENTS AND IMPLICATIONS

A. *Passive weight-support*

Most of the current rehabilitation robots provide gravity support actively by using the same actuators that move the exoskeleton. Passive weight support has the potential of improving the system performance and safety. The control can be simplified, and weight, size and torque demand of the actuators as well as total power consumption, reduced. An additional advantage of using a passive weight-support is that the active exoskeleton can eventually be used as a fully passive device. Nevertheless, it is worth noting that the design becomes more complex since an additional mechanism is added to the active exoskeleton. The implementation of a passive weight-support mechanism with a 3,1 configuration becomes challenging considering that the springs are not only acting in a two-dimensional vertical plane (like in the case of the T-Wrex), but in three-dimensional space (3D).

B. *Suitable for integration in active exoskeletons*

The proposed balancing system has to be integrated in an active exoskeleton and therefore, the mechanism design needs to provide the required space for the location of the actuators. As in the majority of current active exoskeletons we envision to actuate every DOF independently. It is worth noting that the use of a passive weight-support will reduce the required actuator power and consequently the size and weight of the actuators.

C. *Maximum freedom of movement*

In most robot rehabilitation therapies, patients are asked to perform functional movements, mimicking activities of daily living. For such a wide variety of movements it is essential that the exoskeleton and, especially in this case the weight support system do not restrict the arm ROM. From this perspective, it is important to realize that the shoulder joint does not only have three rotational DOFs but also two translational DOF.

The joint alignment between the human and the exoskeleton is another important aspect of the design to prevent pain in the joints and in the surrounding soft tissue. One solution is to perfectly align the joints although this is very time-consuming. Stienen et al. [22] proposed a self-aligning mechanism based on the decoupling of joint rotations and translations to overcome this problem.

D. *Scalable and personalized compensation*

Humans present a wide variety of arm dimensions, therefore it is important that the exoskeleton can adapt to different arm lengths and diameters. In addition, rehabilitation therapy [7], [8] require the gradually adjustment of gravity compensation from no arm weight support to full compensation.

E. *Overall implications*

Together, the requirement of passive weight-support, suitable for integration in active exoskeletons, maximum freedom of movement and scalable and personalized compensation, lead us to the development of a perfect balance system based on the working principle of the ABA mechanism with two parallelogram mechanism and two ideal-springs.

IV. CONCEPTUAL DESIGN

After evaluating several concepts, we decided to use the previously described ABA mechanism as a reference for the design of the perfect balance system for active exoskeletons. The ABA is a mechanism that resembles the motion of the human arm and therefore operates in the centerline of the upper arm and forearm segments (Fig. 5). The ABA mechanism has to be re-designed in such a way that operates adjacent to the arm, provides the natural arm ROM for the performance of ADLs, and provides the required gravity compensation forces to support the combined weight of the patient's arm and of the active exoskeleton.

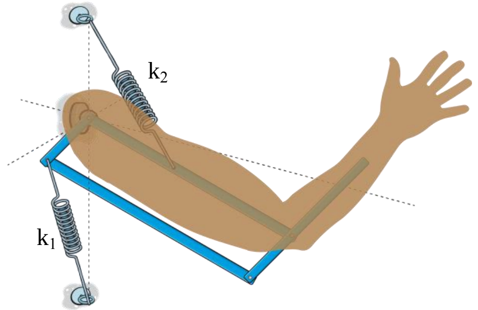

Fig. 5. The ABA is a mechanism that resembles the motion of the human arm and therefore operates in the centerline of the upper and forearm segments.

For simplification, ideal springs (i.e. zero-length springs with linear behavior) are used in this conceptual design and the weight of the mechanism is not taken into account, since this can be easily accounted later using the methods described in [17][18]. Only the weight of the upper arm and forearm segments are considered.

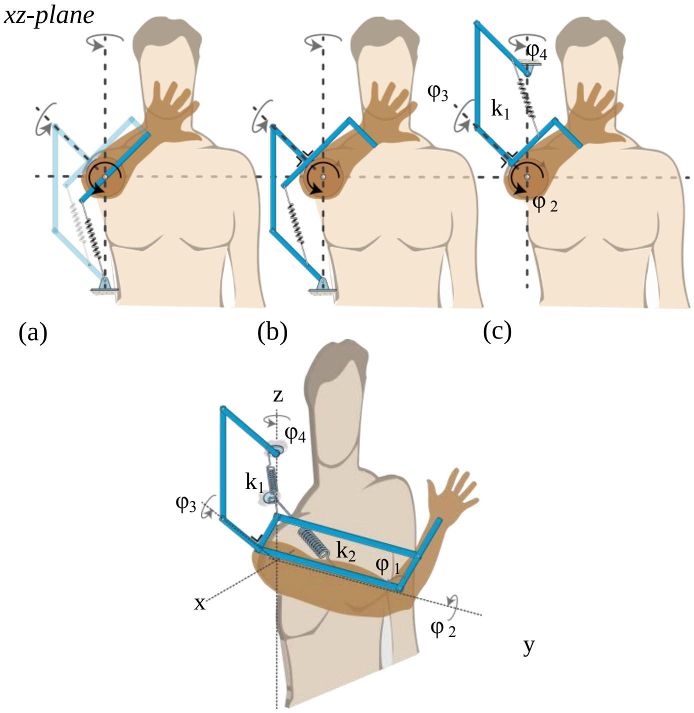

Fig. 6. Modified ABA mechanism. (d) 3D view of the modified ABA mechanism. (a) This is a front view of the ABA (Fig 5.). The balancing mechanism has to be placed adjacent to the arm. (b) A new parallelogram is added to the system perpendicular to the vertical plane (xz) of the arm in order to create a virtual center of rotation around the centerline of the upper arm. (c) The new parallelogram is flipped over and attached to the ground over the shoulder joint to avoid interference with the human arm. Note that in (a) (b) and (c) spring k_2 is not shown for clarity.

In order to be able to place the balancing mechanism adjacent to the arm, a new parallelogram perpendicular to the vertical plane of the arm is added as shown in Fig. 6b to create a virtual rotation around the centerline of the upper arm. However, if the parallelogram is attached to the ground below the shoulder (Fig. 6b and 6c) this will interfere with the arm movement. Therefore, the parallelogram is vertically flipped over and attached to the ground above the shoulder joint (Fig. 6d) where no interference can occur. Note that in Fig. 6a, 6b and 6c spring k_2 is not shown for clarity.

V. CONCEPTUAL DESIGN VALIDATION

To validate if the conceptual design of the balancing mechanism was capable of statically balance the weight of the arm a 3D dynamic simulation of the system was carried out in MSC.Adams™ (Fig. 7). The beams and springs where modeled with no mass. The arm mass was placed at the centerline of the forearm segment. The stiffness of the springs where calculated using (2). The results of this simulation showed a perfect static balance in every position. No additional images are provided since the results of the simulation were all static situations regardless of the system orientation.

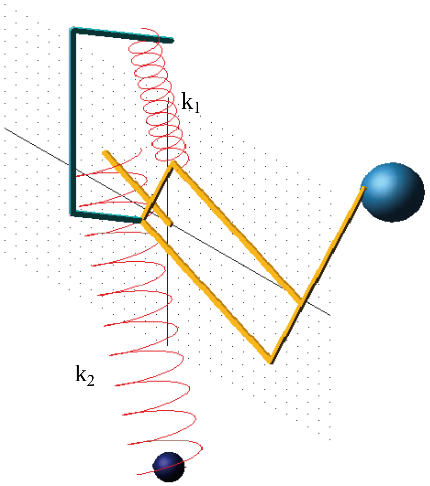

Fig. 7. Outcome of the 3D dynamic simulation of the balancing system carried out in MSC.Adams™. The mechanism was statically balanced regardless of the system orientation. Note that for the 3D dynamic simulation spring k_2 was attached at the bottom ground to have a clearer view. This change does not affect the result as it is equivalent to the original orientation.

VI. MECHANICAL DESIGN DESCRIPTION

After the conceptual design was validated, a 3D mechanical model was created in Solidworks® to evaluate the technical feasibility and bring the design to the prototyping phase (Fig. 10). A schematic view of the kinematic architecture of the proposed balancing system is shown in Fig. 8, where the blue cylinders indicate the possible location of the actuators. There are three rotational DOFs (φ_2, φ_3 and φ_4) for the shoulder joint movements and one (φ_1) for the flexion and extension of the elbow joint.

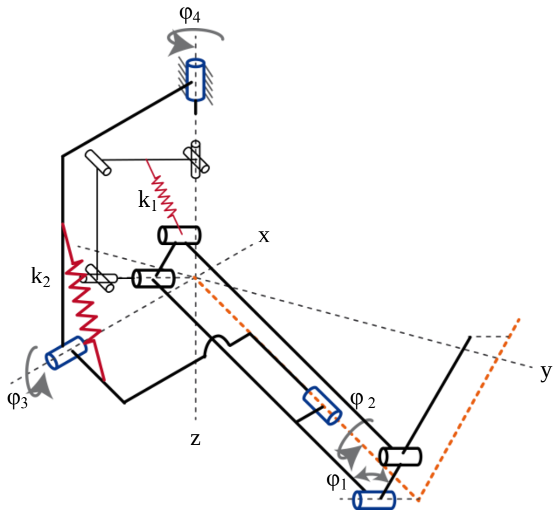

Fig. 8. Schematic representation of the kinematic architecture of the perfect balance system. The blue joints indicate the actuated axes. φ_i indicate the rotational DOFs. Rotational DOF φ_4 is attached to a linkage. Note that the axis of φ_2 is a virtual axis of rotation.

This mechanical design replaces the rigid parallelograms of the conceptual design for cables and pulleys (pseudo parallelogram [23]) which offer the same function as the rigid links of a parallelogram [22]. The advantage of using pseudo parallelograms is that weight and size are reduced leading to a more compact design. In the case of the upper arm pseudo parallelogram, three more pulleys are added to allow upper arm length adjustments (Fig. 9).

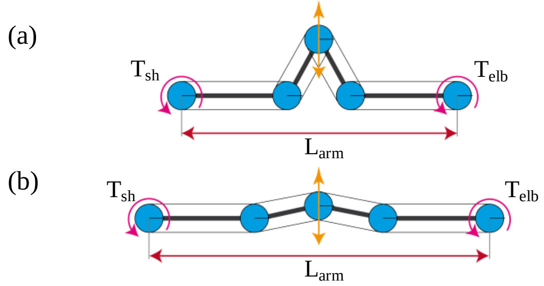

Fig. 9. Length adjustment mechanism. Adding three more wheels to the pseudo parallelogram enables the exoskeleton to adjust to different upper arm lengths (L_{arm}). (a) configuration for short lengths and (b) configuration for long lengths. Note that the torque (T_{el} and T_{sh}) and orientation of the wheels at the ends of the length adjustment mechanism are transmitted through the cable and pulleys as in the case of a parallelogram mechanism. This system is integrated in the tubes adjacent to the human arm (Fig. 10). Spring k_1 is attached to the pulley in the shoulder joint (J_{sh})which has the same orientation as the elbow joint φ_1 (J_{elb}).

The balancing mechanism is mounted at the side of the arm using two circular cuffs. A double parallelogram is mounted to the upper arm cuff (perpendicular to the longitudinal axis of the upper arm) to allow the internal-external rotation of the upper arm. This design is similar to the one used in the Limpact [9], but it could easily be replaced with an upper arm cuff as used by most other exoskeletons. The wrist cuff contains a rotational semicircular guiding that allows pronation-supination of the forearm.

Another important aspect of the design is that the exoskeleton is not directly attached to the ground but to an external mechanism (e.g. double parallelepiped [22]) which can translate freely in 3D space. This additional mechanism prevents the user from axes misalignment and the consequent reaction forces on the human joints.

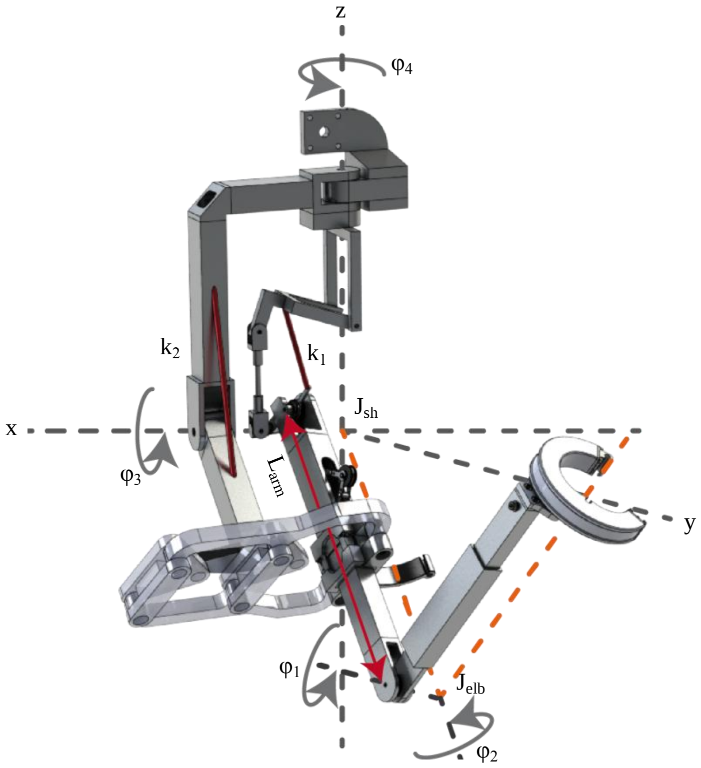

Fig. 10. A 3D view of the mechanical design created in Solidworks®. The balancing mechanism is mounted at the side of the arm using two circular cuffs. The grey dotted line indicates the centerline of the upper and forearm segments. The red cables are connected to the springs which are hidden inside the exoskeleton structure. The upper arm and forearm length can be adjusted by sliding the tubes in and out. The pseudo parallelogram of Fig. 9 is integrated in the tube alongside the centerline between the shoulder (J_{sh}) and elbow joint (J_{elb}). The red arrow indicates the adjustable length of the arm (L_{arm}).

VII. DISCUSSION AND CONCLUSIONS

Gravity compensation is an important aspect of rehabilitation robotics because of its direct effect on the comfort of the patient. Additionally, arm weight support is a common strategy used in upper-extremity therapy. According to the revised literature, most current rehabilitation robots use active methods to provide gravity compensation. We believe that passive weight support presents considerable advantages that can substantially improve the performance of rehabilitation robots: it can simplify the control, reduce the actuator torque demand, lower the power consumption and lead to improved dynamic performance of the rehabilitation robot. An additional advantage of using a passive weight-support is that the active exoskeleton can eventually be used as a fully passive device.

However, while active systems can simply rely on the same actuators that move the exoskeleton, the strategy based on passive weight-support is more complex since an additional mechanism is added to the active exoskeleton.

The proposed balancing system is well suited to compensate the combined gravitational forces of the patient's arm and of the robot while still allowing for direct control of the shoulder and elbow rotations when active actuators are added. The mechanism presents three rotational DOFs at the shoulder and one at the elbow, which mimic the natural arm rotations. This configuration of the DOFs, in contrast to exoskeletons like the T-Wrex [15], allows the upper arm segment of the exoskeleton to be directly connected to the human arm.

Compared to the external balanced springs mechanisms of the Dampace [20], this mechanism offers an integrated weight support into the exoskeleton itself with only two ideal springs, which makes the design more compact. Furthermore, since no angled vertical cables are used there will not be any non-linarites of the compensating forces in the working volume.

The results from the 3D dynamic simulation carried out in MSC.Adams™ validate the balancing quality of the proposed statically balanced mechanism. Furthermore, the detailed mechanical model created in Solidworks® shows that the mechanism is technically feasible to be manufactured.

While this study presents a new perfect balance system for active upper-extremity exoskeletons, some important questions such as the effects on the system performance when the actuators are added, or the actual patient's comfort; remain open. To answer this kind of questions, a comprehensive performance evaluation of a working prototype is required.

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